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LCA FOR AGRICULTURE

Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling

Adrian G. Williams · Eric Audsley · Daniel L. Sandars

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Abstract
Background, aims and scope Food production is essential to life. Modern farming uses considerable resources to produce arable crops. Analysing the environmental burdens of alternative crop production methods is a vital tool for policymakers. The paper describes the production burdens (calculated by life cycle analysis) of three key arable crops: bread wheat, oilseed rape and potatoes as grown in England and Wales using organic and non-organic (contemporary conventional) systems. Resource use (e.g. abiotic and energy) and burdens from emissions are included (e.g. global warming potential on a 100-year basis, global warming potential (GWP), and eutrophication and acidification potentials).
Methods Crop production was analysed, using systems models, so that the effects of factors like changing N fertiliser application rates or irrigation could be examined. Emissions of nitrate were derived from a simulation model in which soil organic N was driven to steady state so that all long-term effects were properly accounted for. Yield response curves to N were similarly derived from long-term experiments. Crop nutrient inputs and plant protection applications were derived from national survey data and the literature. All major inputs were accounted for including fertiliser extraction, manufacture and delivery; pesticide manufacture; field fuel use; machinery and building manufacture; crop drying, cooling and storage. The current balance of production systems were found from survey data. The weighted mean national production was calculated from a combination of three rainfall levels and soil textures. The system boundary is the farm gate. The functional unit is 1 t marketable fresh weight of each product.
Results and discussion The primary energy needs for the producing the three main crops were 2.4, 4.9 and 1.4 GJ/t for bread wheat, oilseed rape and potatoes, respectively. When expressed in terms of dry matter, protein or energy, wheat incurred smaller burdens than oilseed rape, which incurred lower burdens than potatoes. The crops do, of course, all play different roles. Organically produced bread wheat needed about 80% of the energy of non-organic, while organic potatoes needed 13% more energy than non-organically produced ones. While pesticide use was always lower in organic production, other burdens were generally inconsistently higher or lower. Land occupation was always higher for organic production. Lower fertiliser use (and hence energy use) in organic systems is offset by more energy for fieldwork and lower yields. Main crop potato energy needs are dominated by cold storage. Reducing the N application rate for bread wheat production reduces energy use and GWP. The optimum for energy is with N at about 70% of the current level. It seems to be lower for GWP, but the sub-models used are beyond their range of reliability. The results are generally of the same order as those from other European studies.
Conclusions Arable crop production depends heavily on fossil fuel in current major production systems. The emissions causing GWP are very dependent on nitrous oxide, more so than fuel consumption. That, together with emissions of ammonia and nitrate, means that agriculture has a C-N footprint rather than the C footprint that typifies most industrial life.
Recommendations and perspectives With the large influence of nitrous oxide on GWP, evaluation of nitrous oxide emissions by another method, e.g. crop-soil simulation modelling instead of the more rigid IPCC method would improve the robustness of the analysis. The transition between

A. G. Williams (✉) · E. Audsley · D. L. Sandars
Natural Resources Management Centre, Cranfield University, Cranfield,
Bedford MK43 OAL, UK
e-mail: adrian.williams@cranfield.ac.uk

farming systems was not included in this study, but there could be short to medium term benefits of converting from non-organic to organic methods that should be evaluated. System modelling allows alternative production methods to be readily explored and this greatly enhances LCA methodology.

Keywords Acidification · Agriculture · Arable · Energy · Environmental impact · Eutrophication · Global warming potential (GWP) · Nitrate · Organic · Simulation model · System

1 Introduction

A study of arable crop production in England and Wales was conducted as part of the government's programme on sustainability. It was conducted for the benefit of policy-makers and stakeholders so that alternative production scenarios could be systematically examined such as: increasing the proportion of organic production, different tillage methods, reducing fertiliser application rates. This paper covers the major commodities of bread wheat, potatoes and oilseed rape and uses standard life cycle analysis (LCA) together with system modelling. Results are presented at the national level.

Other research has investigated crop production in Europe using LCA. (Audsley et al. 1997) used pan-European data in a study aimed at harmonising agricultural LCA methods and wheat was a case study. (Cederberg 1998) included wheat, maize and soya as feeds. (Charles et al. 2006) studied wheat grown with different intensities of production (Charles et al. 2006). (van der Werf et al. 2005) analysed wheat, barley, soya, maize, sunflower and more in a study of pig feed. Rape has been studied mainly with the perspective of the oil for use as a biofuel. Maize production has been analysed both as part of wider studies on animal feed in Europe (Cederberg 1998; Charles et al. 2006) and as a bio-energy crop in the USA.

Previous studies have used specific data to study alternative systems. This limits the analysis to these systems. In this paper, we adopt a different approach using system models. In the first instance, national production is a combination of proportions of distinct systems—thus ploughing, minimum tillage, direct drilling—which can be altered. Secondly, systems models are used to represent responses to changes—thus level of nitrogen, irrigation or increased yield due to the breeding of new varieties of a crop. In this way, new scenarios can be defined on continuous scales of change from the present.

The goals of the study were to calculate the environmental burdens of producing bread what, potatoes and oilseed rape in England and Wales at a national level, but within a system model structure that allows alternative production methods to be easily and systematically investigated.

2 Methods

2.1 Functional units

The functional unit is 1 t of fresh weight of each product, standardised to 86% dry matter for wheat, 92.5% for rape and 20% for potatoes. Bread wheat produced non-organically contained 13.5% crude protein (CP), but organic bread wheat cannot achieve that level and wheat for bread is accepted at 12.5% CP. Potatoes are grown in three main types: maincrop, first earlies and second earlies, so that the commodity is defined as a basket of each type scaled by national proportions.

2.2 System boundary

The system boundary is the farm gate, but all crop storage, cooling and drying prior to sale are included within the virtual farm gate (for example, central grain storage facilities, but not processor's storage). Soil processes were included to a depth of 0.3 m.

2.3 Long-term approach

In order to follow properly the fate of all mass and energy flows into and out of the system boundary, a long-term approach was needed in the analysis. Thus a build-up or depletion of plant nutrients (inorganic or organic, particularly N) is not permitted and yields must be sustained by the long-term nutrient supply. The supply of a major nutrient to a field must balance the off take and emission to the environment. Thus, every crop bears the burden of supplying the nutrient it removes. Long-term also implies that the transition from one production system to another is not included, e.g. non-organic to organic conversion and the change in soil carbon status. In both organic and non-organic crop production, rotations, tillage and spray use were defined that would achieve technically sustainable yields. The arbitrary removal of, for example, a spray application or weed control cultivation step might incur no yield loss in 1 year, but would progressively lead to long-term yield loss.

2.4 National context

Crop production was represented at a national scale by considering a combination of nine soil texture and rainfalls: clay, loam and sand; 587, 675 and 776 mm. The national distributions were established by (Williams et al. 2006) to provide weighted average national production, including allowances for favoured soil types for particular crops.

2.5 Crop rotations

Crops are grown in a variety of rotations, while this project aimed to determine the burdens of producing specific commodities. The growth of the crops was analysed in the context of representative rotations, implying that the crop receives some benefits such as reduced disease incidence and rotational plant nutrient transfers.

2.6 Crop production methods

The same approach was use to model all the crops, with differences in the detail. The main sources of agricultural burdens for field crop production are: diesel for cultivation, chemical and fertiliser applications, irrigation and harvesting; drying and cooling crops; production of fertilisers, pesticides and machinery; construction and maintenance of buildings for crops and machinery; direct soil-crop emissions to air and water (like nitrate, nitrous oxide and ammonia) and land occupation. All except land occupation involve energy and abiotic resource use and involve some gaseous and aquatic emissions. Crops can be grown organically or non-organically, which have significantly different production systems and are analysed separately. The sum of non-organic methods represents contemporary conventional production. Full details are given in (Williams et al. 2006) and the main points are presented here.

The application of animal manures is specifically excluded. Manures represent an output from livestock systems which displace the need for fertilisers. As the avoided burden of fertiliser production is a benefit to livestock systems, their impact on arable production is zero—although care has to be taken to ensure that the artificial fertiliser requirement of the crops is appropriately increased above survey data. A consequence for organic crops is that they must be grown in a stockless rotation, using fertility building sacrificial crops, and in this case animal manures also displace this land occupation.

3 Data

3.1 Field operations

All arable crops require: seed bed establishment; crop protection (weeds and diseases); fertilisation; irrigation (potatoes only), harvesting and crop storage drying and/or cooling.

3.1.1 Seed bed establishment

Methods of soil cultivation were divided into three methods, namely plough-based, reduced cultivation and direct drilling. The number of passes of secondary cultivation operations depends on soil texture (Chamen and Audsley 1993) and greater energy is needed for tillage of heavier soils (Audsley 1999). The operations used in contemporary farming were derived from the Silsoe Whole Farm Model (Audsley 1981, 1999; Soil Management 2005) and from details from a commercial farming group. Data on fuel used came from 13 sources (reviewed by (Williams et al. 2006)). These were linked with data on tractor and field machinery weights, work rates and life spans to derive overall primary energy requirements (and associated burdens) for field operations using the method of (Audsley et al. 1997).

Primary energy ranged from 470 MJ/ha for direct drilling on sandy soils to 5,210 MJ/ha for ploughing on clay. Potatoes require deeper ploughing (25% extra energy) and only plough based tillage is used. This and the extra operations needed, increases the total energy for establishing potatoes on loam by 84%.

In organic crops, ploughing is the norm, because reduced tillage and direct drilling require pesticides. However, some crops in organic rotations are undersown.

3.1.2 Crop protection

Plant protection involves both rotations and some chemical applications. The numbers of passes with a sprayer and numbers of doses per crop were obtained from the Pesticide Usage Surveys (Garthwaite et al. 2005). Additional light cultivations for weed control are used in organic crops for weed and disease control. Potato blight control, using copper based products, is permitted in a derogation, otherwise pesticides are not used in organic crop production.

3.1.3 Fertiliser application and harvesting

Synthetic and mineral fertilisers are applied using relatively little energy (110 MJ/ha). If cereal straw is not being baled, then the combine harvester will also chop the straw (using more energy for this). The burdens of baling and carting straw are allocated to the straw, if harvested. Combine harvesting (with straw chopping) takes 1,130 MJ/ha while potato harvesting needs 3,140 MJ/ha.

3.1.4 Crop storage, cooling and drying

All crop storage is considered to take place within the farm gate, even though in practice some takes place physically elsewhere. The energy for constructing, maintaining and demolishing a grain store were estimated using the method of (Garthwaite et al. 2005), but with their data supplemented by local expert opinion, using a typical mean storage requirement of 0.4 m^2 t^{-1} (Table 1).

In the UK, grain is often dried after harvest. Wheat is dried to 86% dry matter (DM) and rape to 92.5% DM.

Table 1 Total numbers of pesticide applications for main crops

Crop	Details	Non-organic			Organic		
		Passes/ha	Dose-ha	Active ingredients, kg/ha	Passes/ha	Dose-ha	Active ingredients, kg/ha
Potatoes	Main	12	14	9.5	2.5	2.5	1.7
	1st Earlies	8.3	9.9	6.7	1	1	0.7
	2nd Earlies	12	14	9.5	2.5	2.5	1.7
Bread Wheat	Plough-based	5.2	6.5	4.4	2.5	2.5	1.7
	Reduced cultivation	6.0	7.5	5.1	N.A.	N.A.	
	Direct drilling	6.6	8.5	5.8	N.A.	N.A.	
Oilseed rape	Plough-based	4.8	4.4	3.0	N.A.	N.A.	
	Reduced cultivation	5.1	5.6	3.8	N.A.	N.A.	
	Direct drilling	6.4	5.8	3.9	N.A.	N.A.	

Each pass contains one or more active ingredients (a.i.) frequently at less than the full dose of that a.i. A dose is the sum of the fractions of full dose applied to the crop. Note that this independent of the toxicity of the ingredients

N.A. not applicable

During the harvest period the harvested grain DM varies with weather conditions. In good years, no grain needs drying. Data on long-term harvested wheat grain DM came from Rothamsted's *Broadbalk* dataset for 1971 to 2001. These were used to calculate the energy needed for grain drying. The mean specific energy requirement for evaporating water in representative grain driers was estimated to be 4.7 MJ/kg water (McLean 1989; Brooker et al. 1992). The drying requirements for other crops were calculated by relating their equilibrium moisture curves (Nellist 1998) to that of wheat so that the same distribution data from *Broadbalk* could be used as a proxy for DM at harvesting.

The results show that the energy needed for drying wheat from 1991 to 2001 was only 45% of that from 1971 to 2001, perhaps reflecting climate change or changed managerial practices resulting from higher fuel prices. Results from these 10 years were thus used (Table 2). Some crops are cooled by ventilating with ambient air and average values were derived from data in (McLean 1989) and (Scotford et al. 1996). It was assumed that 1/12 of grain was sold direct from combined harvesters for immediate use and thus did not need storing cooling or drying.

Table 2 Primary energy used for crop storage, cooling and drying grain

Item	Wheat	Rape
Building itself	11	11
Cooling	1.2	4.1
Drying	133	158

All values relate to energy per unit mass fresh weight (after drying) at standard dry matter contents, MJ/*t*

Potato storage Earlies are harvested and sold directly. Main crop potatoes may be stored for over a year (Defra 2004). The market price for main crop potatoes falls in the spring and most are removed from stores by May, but some are stored for processing and catering through to next harvest. Most potatoes are stored in temperature controlled environments using ambient ventilation or refrigeration, while a small proportion is stored in clamps (Anderson et al. 2002).

The energy needed to cool potatoes was estimated using a model of the expected rates of emptying of stores and the specific energy needs of store types (Anderson et al. 2002; Anon 1999; Beukema and van der Zaag 1990; Bishop and Maunder 1980). It was assumed that 10% of organic main crop is sold directly (e.g. vegetable boxes). This would not remain valid if organic became the main production system rather than its current niche. Cooling energy was thus scaled in proportion to the level of organic production so that the energy demands for 100% organic and non-organic approach each other. This avoids the possibility of extrapolating a system that is currently a niche into a distribution system that operates in a different way (Table 3).

3.2 Production of inputs

3.2.1 Pesticide manufacturing energy

The manufacturing energy for pesticides was derived from (Audsley et al. 1997) and (Garthwaite et al. 2005). Values were assigned for different types of pesticide (and growth regulators). The mean primary energy requirement for wheat, rape and potatoes were 144, 121 and 220 MJ/dose ha, respectively.

Table 3 Energy consumption during potato storage (primary energy per t)

Item	National total for non-organic, %	Organic (estimated), %	Building, MJ (as primary energy)	Electricity (as primary energy), MJ	Weighted primary use, non-organic, MJ	Weighted primary use, organic, MJ
Outdoor clamps	0.2	0.7			0.0	0.0
Unventilated building	2.7	9.3	11		0.3	1.0
Ventilated building	35.8	33.2	11	224	84	78
Refrigerated building	61.3	56.8	11	929	576	534
Total	100.0	100.0			660	613

3.2.2 Fertiliser manufacturing

The four main plant nutrients (N, P, K and S) and soil pH adjustment through lime were included in the analysis. There are systematic differences between non-organic and organic methods. Organic nitrogen is derived directly (or indirectly as manure or compost) from nitrogen fixation by legumes. Non-organic N is mainly obtained from ammonia-derived materials using the Bosch-Haber process in which natural gas is used both as an energy source and feedstock. Both systems receive atmospheric deposition of N, P and K must be added in organic systems to balance offtake, but must be from sources such as rocks with a minimum of physical processing. Lime is used in both systems, but it was assumed that burnt lime was not used in organic production.

The burdens for producing, packing and delivering fertilisers (Table 4) were derived from 20 sources that were reviewed by (Williams et al. 2006). The main burdens relate to energy use (e.g. for converting N_2 to NH_3 or quarrying and transporting minerals). A specific extra term is needed for nitrous oxide (N_2O) from nitric acid production, which is used for nitrate based fertilisers.

3.2.3 Nitrogen supply in organic systems

Any actual farm may use manure of compost to provide fertility, but the nitrogen supply comes mainly (directly or indirectly via manure) from nitrogen fixing crops. We debit the burdens of manure to animal production in our work, so excluded manure from this analysis to be comparable with non-organic cropping and to establish what the crop needs are.

A representative stockless organic rotation consists of 2 years of a fertility building clover crop, wheat or potatoes, spring barley, winter beans, and spring oats. Forage rye is planted as a cover before the spring crops. If only 1 year of clover was grown, subsequent yields would be reduced owing to the lower N supply, although land occupation would superficially fall (i.e. less land needed for fertility building, but a lower N supply would reduce yields and could actually increase the land needed per ton of crop). The additional burdens consist of additional ploughing and maintenance operations and land occupation including land for seed production. The additional ploughing required per cash crop is a factor of 1.25 times the non-organic crop and the additional land required is a factor of 1.525. However, the additional requirement should be applied per the nitrogen requirement of the cash crops.

It is estimated from data (Soil Association 2003) that organic farms import compost annually into arable soils at a rate of 1.4 t/ha. The burdens of composting have two main sources: energy for collection and turning, and gases emitted during composting. A simplifying assumption was that no leaching takes place from compost heaps, and all N losses are gaseous. Energy and emissions were estimated (Table 5) using data from 15 sources as reviewed by (Williams et al. 2006).

3.3 Use of inputs

3.3.1 P, K and S supply

Farmers supply P and K to maintain a particular soil status over time, but not necessarily to the specific crop. The model assumes that P, K and S are supplied equal to the off take in the crop (and any losses to the environment). However, farmers add P to potatoes in excess of plant off take because the crop needs (responds to) a higher level in the soil. The burden of P production is born by potatoes and the surplus is allocated to other crops grown in such rotations in proportion to the national areas and yields. Atmospheric deposition of S was accounted for.

3.3.2 N supply

The effects of fertiliser nitrogen on wheat yield (and protein content) were modelled using data from Rothamsted's long-term *Broadbalk* plots, where the fertiliser treatments have been applied for many years, so that true long-term effects can be seen. N application rates range from 0 to 288 kg N/ha. Short-term fertiliser experiments are confounded by previous cropping and fertiliser use so that low inputs reduce the fertiliser status of the soil and the yields are no technically

Table 4 Main burdens for producing, packing and delivering main types of fertilisers

Item	Unit	Primary energy, MJ	Global warming potential, kg CO_2 equiv.	Eutrophication Potential, g PO_4^{3-} equiv.	Acidification potential, g SO_2 equiv.	Abiotic resource use, g Sb equiv.	N_2O-N, to air, g
Ammonium nitrate as N	kg N as N	41	7.2	0.50	4.7	23	9.4
Urea as N	kg N as N	49	3.5	0.54	5.3	23	0.025
Calcium ammonium nitrate as N	kg N as N	43	7.4	0.55	5.3	21	9.4
Ammonium sulphate as N	kg N as N	42	3.0	0.52	5.3	20	0.022
Triple super phosphate as P	kg P as P	19	1.2	0.74	8.1	15	0.012
Single super phosphate as P	kg P as P	13	0.60	0.57	6.6	16	0.0094
Rock P from 25% P_2O_5 Tunisian as P	kg P as P	15	1.1	0.97	13	17	0.012
K fertiliser (Muriate of potash) as K	kg K as K	5.7	0.53	0.30	7.2	3.9	0.0056
Rock K as K	kg K as K	15	0.86	1.40	8.8	17	0.0094
Gypsum (quarried) as S	kg S as S	5.5	0.35	0.58	3.7	5.9	0.0031
Gypsum from flue gas desulphurisation as S	kg S as S	1.9	0.11	0.14	0.9	4.2	0.0020
Limestone as Ca (39% Ca in product)[a]	kg Ca	2.3	0.15	0.26	1.6	2.4	0.0014
Burnt lime (or chalk) (60% Ca in product) as Ca	kg Ca	8.5	0.23	0.20	2.4	5.1	0.0020
Weighted lime usage for non-organic crops as Ca	kg Ca	3.2	0.16	0.25	1.7	2.8	0.0015

EP Eutrophication potential, *AP* acidification potential, *ARU* abiotic resource use

[a] Includes CO_2 emitted from soil once neutralised

sustainable. The increase in the grain yield (Y) in response to applied N was well characterised by a linear-exponential curve:

$$Y = a - b\exp(-cN) - dN.$$

The nitrogen off take in grain is characterised by a logistic growth curve:

$$Y = a + b/(1 + \exp(-c(N - d))).$$

The same forms of equation applied to straw (Table 6). Using the expressions, yields change mechanistically in response to changes in N.

The *Broadbalk* data were for one type of feed wheat on one specific soil. Further adjustments were made to allow for differences between bread and feed wheat protein concentrations using NIAB (www.niab.com) variety data and for the effect of soil type on yield. Bread varieties typically yield 5% to 10% less than feed ones, but contain

Table 5 Main burdens of composting residues

Item	Unit	Primary energy, MJ	Global warming potential, kg CO_2 equiv.	Eutrophication potential, g PO_4^{3-} equiv.	Acidification potential, g SO_2 equiv.	Abiotic resource use, g Sb equiv.	N_2O-N, to air, g
Imported compost (fresh weight basis and energy based only)	*t*	80	5.10	7.1	43	170	0.094
Main compost nutrients in imported compost: N, P, K or S (energy based)	kg	8.6	0.55	0.76	4.6	18	0.010
Cattle manure composted–gaseous emissions	kg N		4.40	68	300		3.6
Pig manure composted–gaseous emissions	kg N		1.30	570	2,500		2.0
Poultry manure (no bedding) composted–gaseous emissions	kg N		6.10	780	3,400		11
Poultry manure (with bedding) composted – gaseous emissions	kg N		4.40	620	2,800		9.2

Table 6 Fitted parameters for relating crop yields to nitrogen fertiliser application rate

Crop	a	b	c	d	Nominal mean N application rate, kg/ha
Wheat grain, t/ha	453.7	452.6	0.000626	0.237	208
Wheat straw, t/ha	461.6	460.8	0.000333	0.135	
Wheat grain N offtake, g/ha	−37.35	204.9	0.0131	83.64	
Oilseed rape	203.55	−203.03	0.000614	−0.104	200
Potatoes-main	3144.5	−3136.4	0.000760	−1.995	220
Potatoes-1st	1628.3	−1624.1	0.000832	−1.131	170
Potatoes-2nd	2976.5	−2,968.9	0.000832	−2.067	200

more protein. Organic farmers (with lower soil nitrogen supply) need to choose the highest protein varieties to be able to achieve over 12% crude protein with any reliability and often grow spring wheat, which has a higher protein concentration, but is even lower yielding. Yield responses to soil texture were made using coefficients derived by (Audsley 1981). Analogous relationships were derived for potatoes and rape (see Table 6). The N supplies for crops grown organically were inferred from those needed to obtain the same yield non-organically.

3.3.3 Potato irrigation

Potatoes are often irrigated, with the amount depending on the weather and soil type. (Weatherhead et al. 1997) showed that irrigation increased yield by 25% for main crop potatoes. Main crop potatoes use more irrigation than first earlies, which may be harvested before the summer soil water deficit sets in. A relationship for yield in terms of proportion of the area irrigated was developed derived from (Weatherhead et al. 1997) and (Weatherhead and Danert 2001). The yield at any level of irrigation, μ, is:

$$Y(\mu) = \frac{((\gamma_{100} - 1)\mu + 1)Y_m}{((\gamma_{100} - 1)\mu_m + 1)}$$

μ_m is the current level of irrigation, Y_m is the yield at the current level of irrigation (γ_{100}). Parameter values and yield responses are given in Table 7. Long-term yield data were obtained from government statistics (Defra 2004), being 19.1 t/ha for earlies and 43.5 t/ha for maincrop. It was assumed that organic potato production uses 10% of the irrigation as non-organic as organic farmers try minimise any inputs.

3.4 Yield penalties

3.4.1 Sub-soiling

Sub-soiling is deep cultivation with narrow tines, used to break plough pans or to loosen compacted soils. It was assumed that if sub-soiling is too infrequent on some soils (one third of all), there is a yield loss. This happens when the interval (1) exceeds i_0 years. Below this interval, there is no yield loss or gain. Maximum yield loss was assumed to be 10%, with i_0=3 years.

3.4.2 Reduced tillage and direct drilling

There is controversy about the long-term yields of crops grown without ploughing. Build up of some weeds such as black grass has been suggested as being detrimental, and may cause a move back to ploughing (maybe temporary), although (Robertson et al. 2000) found enhanced yields of wheat with direct drilling. It was decided to assume that long-term yields reductions of 2% and 4% applied to crops grown with reduced tillage and direct drilling respectively, but with increased use of chemicals for weed control.

3.4.3 Marketable crop yield

Not all wheat intended for breadmaking achieves the quality required. HGCA (2003) reported a survey of the crude

Table 7 Mean irrigation rates, the proportions irrigated, the response to the current proportion irrigated and the average yield of potato growing areas in England

Type of potato	Application rate, mm/year	Current proportion irrigated μ_m, %	γ_{100} (*)	Y_m
First earlies	90 (18)	40 (11)	1.25	19 (21)
Second earlies	105 (xx)	48 (xx)	1.25	42 (xx)
Maincrop	120 (23)	56 (24)	1.25	44 (4)x

Numbers in brackets are coefficients of variation, %

Υ_{100} is the maximum factor by which yield increases through irrigation, Y_m mean yield at the current level of irrigation, μ_m

protein (CP) concentrations in grain after harvest. For example, for the variety *Hereward*, the cumulative distribution CP concentration was 1% at<11.3% CP, 21% at<13.5% CP, 71% at<15.5% CP (with 6% at>15.5% CP), suggesting a normal distribution. Both the *Hereward* and Rothamsted's *Broadbalk* data suggest a standard deviation of about 1% in protein concentration. Organic bread making wheat varieties show a standard deviation of 0.66% protein, with a mean of 12.5%. A standard deviation of 0.6% was thus used to calculate the proportion of crop that met the bread making protein criteria. Wheat may also fail to meet bread making quality by having the wrong Hagberg Index or specific weight. This is typically 4.4% of gross yield and this becomes feed (or non-bread milling) wheat. Wheat that is grown for bread making, but the burdens were allocated between the bread and feed fractions according to their economic value.

Potatoes may be not suitable for human food due to size, quality and damage. The typical non-organic loss rate is 15%. Loss was divided equally into stock feed (12% burdens of human edible crop) and those returned to land (mostly via composting). The typical loss rate of organic potatoes (mainly from slug damage) is 30% (Lampkin et al. 2002; Nix 2002) and can range as high as 50% (Nix 2005).

3.5 Emissions to the environment

3.5.1 Emissions of N

The effects of soil and rainfall on leaching (nitrate to water) and denitrification (nitrogen as N_2 and N_2O to air) were established using the SUNDIAL simulation programme from Rothamsted Research (Smith et al. 1996). A range of non-organic and organic rotations were defined that contained representative crops. Simulations were run for long enough to ensure that the simulated rotations were in steady state, as indicated by the soil organic N fraction being the same at the start and end of a rotation. N inputs come from atmospheric deposition, fertiliser, fixing, seeds, returned roots, straw and haulm. N outputs come from primary crop off take (grain, tubers), secondary crop off take (straw), returned off take (roots, straw and haulm), leached nitrate-N, denitrified-N and N from senescing plants.

The rotations were simulated for nine combinations of soil type and rainfall (clay, loam and sandy soil with rainfall at 587, 675 and 776 mm). Crops were also grown with and without straw incorporation. Yields, which are an input to SUNDIAL, were taken from national averages or standard texts, scaled according soil type using relationships previously developed by (Audsley 1981). Organic crop yields for these simulations were taken from (Lampkin et al. 2002) and varied according to soil type.

Standard N fertiliser inputs for non-organic production were established from RB209 MAFF (2000) and use of the SUNDIAL (in the Fertiliser Recommendation System version). Individual crops were also simulated with N inputs increased or decreased by 20% from these standard values.

For organically grown crops, the initial assumption was made that the yields should be sustainable, using fixed N from the clover lay (with beans in the fifth year), if it could provide sufficient N and not deplete soil reserves. Preliminary runs assessed how well the rotation performed and most crops could achieve their target yields, except for spring oats, which only yielded 3.0 t/ha, rather than the 3.8 t/ha that was forecast. The N fixed was calculated by SUNDIAL as 300 kg/ha over the 2 years of clover, with more fixed in the second year than first year. This was based on standard values from the literature, and agreed as a possible value with the Elm Farm Research Centre.

Analysing the results of these simulations, in the non-organic simulations the N leached at a rotational level was linearly related the whole-rotation N surplus. Allocations were derived for the individual crops within each rotation on the basis of the proportion to the surplus due to each crop. The results were combined to generate linear relationships for each crop from which denitrification and leaching could be reliably calculated for each soil-rain combination from the N surplus for that crop. These coefficients were used in conjunction with crop husbandry data to predict denitrification, leaching and senescence for any given input of N. For field beans, it was concluded that denitrification and leaching losses were a constant for each combination of soil and rainfall.

Exactly the same methods could not be used with organic rotations, because there was not a simple surplus that could be calculated for each crop (most N being fixed at the start of the rotation by clover). Values for the off take and N losses of field beans were taken from the non-organic rotations. The sum of all other losses from a rotation was then allocated to the remaining cash crops in proportion to the useful N off take of each crop for each combination of rainfall and soil texture.

Losses from senescence are generally low (about 2 kg N ha^{-1}) and were assumed to be an equal mixture of NH_3-N and N_2N.

3.5.2 Denitrification to nitrous oxide using the IPCC methodology

SUNDIAL calculates total denitrification, but the major species of concern is N_2O, given its great power in global warming. The Intergovernmental Panel on Climate Change IPCC 2001 method and emission factors, as reported in the UK greenhouse gas inventory (Baggott et al. 2004) was

adopted for land-based emissions. This assumes that most direct inputs of N into soil are associated with an emission of N_2O and each is associated with an emission factor. Direct inputs include: synthetic fertiliser; ploughed-in crop residues; land spreading of animal manures, compost or sewage sludge and direct deposition of manures by grazing animals. Indirect emissions arise from atmospheric deposition of N and leached nitrate. We excluded N fixed by legumes.

3.5.3 Methane oxidation by soil

A credit arises to agricultural land from methane oxidation by methanotrophic soil bacteria. A value of 0.65 kg CH_4 ha^{-1} $year^{-1}$ for all non-organic land was established after an extensive examination of 24 papers literature reviewed by (Williams et al. 2006). This was arbitrarily increased by 25% for organic land on the basis that N fertiliser is not used and some work has shown inhibition of methane oxidation from this. The field evidence for more methane oxidation in organic soil was not, however, found in the literature. The extra land occupied for grass clover leys in organic arable crop production is also credited with methane oxidation capacity.

3.5.4 P and K losses

Losses of P and K by diffuse pollution (and erosion) from non-organic fields were set at 1.5 and 2 kg ha^{-1} respectively. These were reduced by 50% for organic fields in which a lower P and K status was assumed. P and K off takes were derived from crop yields (including straw) and the nutrient concentrations MAFF (1992).

3.6 Allocation of burdens between grain and straw

Grain is harvested by a combine harvester, but straw may be harvested or incorporated. If harvested, additional burdens are incurred by the straw baler, but the actual combine energy is reduced slightly as a straw chopper is not required. Thus, one can calculate the burden attributable to the grain.

The total burdens of producing grain and straw are:

$$T = H + (1 - p_s)I + p_s B + D$$

Then the burden allocated to grain is:

$$G^* = (H + I)\left(Y_g / \left(Y_g + v_s p_s Y_s\right)\right) + D,$$

and the burden allocated to straw is:

$$S^* = \frac{(H + I)\,(v_s p_s Y_s)}{\left(Y_g + v_s p_s Y_s\right)} + p_s(B - I),$$

where H is the vector of burdens of producing grain up to the end of combine harvesting per hectare, I is the vector of burdens of chopping for incorporation for all straw produced, D is the vector of burdens of drying and storage of grain, B is the vector of straw baling burdens for all straw produced, p_s is the proportion of straw baled and harvested, Y_g is the net yield of grain per hectare at standard DM content, Y_s is the yield of straw per hectare (whether harvested or not) at standard DM content, and v_s is the relative value of the straw *prior to baling* versus the grain, typically 0.05.

3.7 Impact assessments

The impact assessment factors were taken from the Institute of Environmental Sciences of Leiden University (CML) found at (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). The CML 1999 problem-oriented approach baseline factors were used for eutrophication and acidification (not including fate) and abiotic resource use together with the IPCC 2001 factors for global warming potential. Land occupation was calculated explicitly from yield data.

4 Results

The gross fresh weight yields of the crops analysed are shown in Table 8 together with the proportions of each crop grown organically.

The results (FW basis) combine the current proportions of current non-organic and organic farming and different

Table 8 Gross yields of crops at national level, t/ha

Bread wheat (0.7%)		Oilseed Rape (0%)		Potatoes (1%)					
				Maincrop		First earlies		Second earlies	
Non-organic	Organic	Non-organic	Organic[a]	Non-organic	Organic	Non-organic	Organic	Non-organic	Organic
7.7	4.1	3.3	1.8	52	35	26	19	48	34

Values in parenthesis show the proportion grown organically

[a] Estimated from the relative yields of organic and non-organic wheat as too little is grown organically to give valid data

Table 9 Main burdens of production of each crop commodity (per t)

Impacts and resources used	Bread wheat	Oilseed rape	Potatoes
Primary energy used, GJ	2.4	4.9	1.4
Global warming potential, t CO_2 equiv.	0.70	1.4	0.20
Eutrophication potential kg PO_4^{3-} equiv.	3.1	8.2	1.0
Acidification potential, kg SO_2 equiv.	3.3	9.0	0.8
Pesticides used, dose ha	0.9	1.5	0.4
Abiotic resource use, kg Sb equiv.	1.5	2.8	0.9
Land occupation, grade 3a equiv., ha	0.14	0.32	0.03
N losses			
NO_3-N, kg	4.3	12	1.7
NH_3-N, kg	1.2	2.4	0.25
N_2O-N, kg	1.0	3.0	0.08
N_2-N, kg	6.8	26	1.1
Irrigation water, m^3			21

current cultivation systems (Table 9). When compared on a DM basis, wheat captures about twice the DM per unit energy of the other crops (Table 10). Wheat is still about 25% more energy efficient in capturing protein than rape, but three times more efficient than potatoes. A similar trend holds for digestible energy (for pigs) of the whole crops (see Table 10). Of course, the three crops fulfil very different functions and rape provides oil (for human food or bio-diesel) as well as a meal for animal feed. Once oil has been extracted from rapeseed, the protein in rapeseed meal incurs about the energy of that in wheat.

4.1 Bread wheat

The contrasts between non-organic and organic arable crop production are well illustrated by bread wheat (Table 11). Organic production uses about 20% less energy than non-organic, while using about three times the land area (including fertility building and cover crops). Although emissions per hectare are sometimes lower from organic, yields are about halved and nitrogen fixing crops are needed, thus burdens in many cases are little changed. Fertiliser production, cultivations and harvesting are the main energy consumers, with fertiliser production dominating non-organic production (53%) and field work dominating organic production (60%). Field operations represents about a quarter of the total energy input to non-organic wheat, with equipment manufacture representing about one third of that energy input. Organic cultivations use more energy per hectare than non-organic as direct drilling or reduced tillage

Table 10 Primary energy used for crop production (grain or tuber only) on four bases (without any further processing)

Basis	Bread wheat	Oilseed rape	Potatoes
GJ/t Dry Matter	2.8	5.2	6.8
GJ/t crude protein	20	25	63
GJ /GJ gross energy	0.15	0.18	0.40
GJ/GJ digestible energy	0.18	0.27	0.57

Table 11 Burdens of producing bread wheat non-organically and organically (per t produced)

Impacts and resources used	Non-organic	Organic
Primary energy used, GJ	2.4	2.0
Global warming potential, t CO_2 equiv.	0.70	0.80
Eutrophication Potential , kg PO_4^{3-} equiv.	3.0	9.3
Acidification Potential, kg SO_2 equiv.	3.3	3.6
Pesticides used, dose	0.92	0.00
Abiotic resource use, kg Sb equiv.	1.5	1.4
Land occupation grade 3a Equiv., ha	0.14	0.41
N losses		
NO_3^--N kg	4.2	18
NH_3-N kg	1.1	1.5
N_2O-N kg	1.0	0.91
N_2-N kg	6.7	12
Primary Energy Usage Proportions		
Field work: Cultivation	20%	60%
Field work: Spraying	3.6%	0.0%
Field work: fertiliser or compost application	2.6%	2.7%
Field work: harvesting	8.4%	21.6%
Crop storage, drying and cooling	5.2%	7.7%
Pesticide manufacture	6.9%	0.0%
Fertiliser manufacture	54%	7.8%
Contributors to global warming potential		
CO_2	23%	16%
CH_4	0.8%	-0.4%
N_2O (direct)	70%	58%
N_2O (via nitrate)	6.9%	27%

Table 12 Effects of some scenarios on the burdens of bread wheat production (per t)

Impacts & resources used	Original	All urea	Reduced cults	75% N fert.	90% clay	+1% protein	+20% yield
Primary energy used, GJ	2.4	2.4	2.3	2.3	2.3	2.5	2.2
Global warming potential, t CO_2 equiv.	0.70	0.56	0.70	0.61	0.64	0.74	0.65
Eutrophication potential , kg PO_4^{3-} equiv.	3.1	3.4	3.1	2.5	2.7	3.2	2.5
Acidification potential , kg SO_2 equiv.	3.3	8.5	3.3	3.1	3.1	3.5	3.0
Pesticides used, dose	0.9	0.9	1.1	1.0	0.8	0.9	0.8
Abiotic resource use, kg Sb equiv.	1.5	1.4	1.4	1.4	1.4	1.5	1.4
Land occupation grade 3a equiv., ha	0.14	0.15	0.15	0.16	0.15	0.14	0.12
N losses							
NO_3^--N kg	4.3	2.8	4.4	3.0	3.6	4.5	3.4
N_2O-N kg	1.2	0.8	1.2	1.0	1.0	1.2	1.1
NH_3-N kg	1.0	3.3	1.0	0.9	0.9	1.1	0.9
N_2-N kg	6.7	4.5	6.9	4.7	6.4	7.1	5.4

is not used. This, together with lower yields and no artificial N fertiliser are why the proportion of energy used in field operations is so much higher. Organic wheat is produced without any pesticides.

Compared with combustion-based industries, fossil fuel use is a minor contributor to global warming potential (GWP, on a 100-year basis) in arable agriculture. The main contributor (80%) is the N_2O-N emissions because they are 400 times more potent than CO_2 (mass basis). Nitrous oxide is emitted as a by-product of the nitrogen cycle in the soil as nitrogen is transformed between organic matter, ammonia and nitrate. The IPCC 1997 method estimates 1.25% of most soil N fluxes are emitted as N_2O-N. This emission is irrespective of whether the N source is as synthetic N or from N fixing, thus the proportions of N_2O emitted are closely related to the crop N supply and are not intrinsically different between organic and non-organic production. Arable methane emissions in the UK are trivial compared with those from animals, especially ruminants.

Scenarios of bread wheat production were investigated (Table 12). Because non-organic represents 99% of production, most of the following applies only to non-organic production.

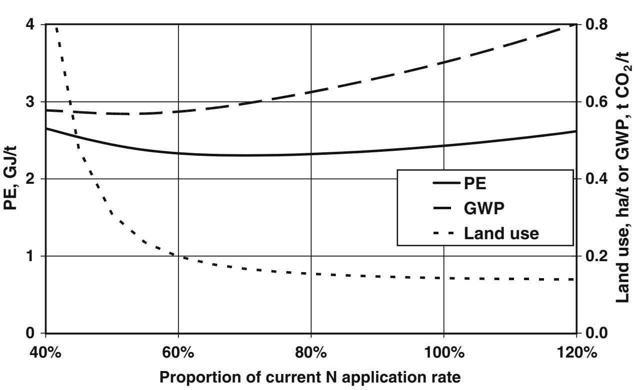

Fig. 1 Effects of changing N fertiliser on burdens of bread wheat production (PE is primary energy and GWP in global warming potential)

Currently, 20% of the fertiliser-N applied to bread wheat is urea. Increasing this to 100%, results in diverse effects. Primary energy (PE) remains effectively constant, but GWP falls by 21%, mainly because of the absence of the specific emission of N_2O associated with nitrate production. Eutrophication potential increases by 11%, but there is a 2.5-fold increase in acidification potential resulting from the large field ammonia emissions. Although urea has a lower specific energy requirement than ammonium nitrate, more has to be applied to maintain the same N supply as ammonium nitrate owing to the large field losses. So, potential gains in reducing PE are cancelled out by higher application rates.

If ploughing was reduced from the current 57% to 0 and replaced by 50% reduced cultivation and 50% direct drilling, PE use falls by 5%. Most other effects are small, but pesticide use is increased by 15% as herbicides are essential features of these lower energy tillage methods.

If plant breeding provides varieties with 1% more protein, the N supply to the crop must be increased, resulting in increases of all major burdens by about 4%. A greater proportion of domestic wheat could, however, be used for bread making, so replacing the need for imports. Importing grain from North America increases PE and GWP by about 28% and 14%, respectively. The model assumes the same nitrogen utilisation efficiency for current and improved varieties.

Breeding new varieties with 20% higher yield, but with the same protein concentration, causes a reduction in all burdens (e.g. PE, GWP and acidification by 8-9% and eutrophication and potential land occupation by 17%). This happens even though 14% more N fertiliser is used. It should be noted that there is normally a negative correlation between increased yield and increased protein in wheat breeds.

Table 13 Comparison of the burdens of producing early, second early and maincrop potatoes (per t), with 1% produced organically

Impacts and resources used	1st Earlies	2nd earlies	Maincrop
Primary energy used, MJ	1.3	0.74	1.5
GWP_{100}, kg 100 year CO_2 equiv.	0.29	0.13	0.17
EP, kg PO_4^{3-} equiv.	2.2	0.58	0.53
AP, kg SO_2 equiv.	1.0	0.62	0.78
Pesticides used, dose ha	0.48	0.35	0.33
ARU, kg antimony equiv.	0.65	0.38	1.1
Land occupation grade 3a Equiv., ha	0.043	0.022	0.021
Irrigation water, m^3	18	13	16
Primary energy usage proportions			
Field work	57%	56%	28%
Crop storage and cooling	0%	0%	49%
Pesticide manufacture	8%	10%	5%
Fertiliser manufacture	34%	34%	18%

Growing wheat on heavier soils increases yields and despite requiring more energy for tillage, burdens are reduced (by a mean of 5%) as the proportion of clay soils used doubled.

If straw is baled rather than being incorporated, it incurs extra burdens for field operations and exported plant nutrients in straw. As straw is a co-product of grain, some of the burdens of grain production are passed to the straw. The effect is a linear decrease in the burdens of grain production (mean of 4%) as the proportion of straw baled increases (from 0 to 100%), reflecting to overall increase in useful produce exported from the field. The effect is similar for both organic and non-organic crops.

The effects of changing the N fertiliser rate are non-linear, reflecting at least partly the linear-exponential yield curve and the effects on protein concentration (Fig. 1). The PE needed for bread wheat reaches a minimum at about 75% of the current rate. Other burdens show similar trends with different minima, but this is the most reliable value because the sub-models used to estimate leaching and total denitrification have been stretched beyond their original domain and the results become less reliable. The yield curve is well within a reliable range. Land occupation increases since both yield and protein concentration fall with less N. At 75% N rate, land occupation increases by 11%, but this increases rapidly with further reductions of N, increasing by 40%, 120% and 560% at 60%, 50% and 40% N rate, respectively. This latter increase in land occupation reflects more the lower protein concentration than reduced yield.

Table 14 Burdens of producing potatoes produced non-organically and organically (per t FW)

Impacts and resources used	Non-organic	Organic
Primary energy used, MJ	1.4	1.6
GWP_{100}, kg 100 year CO_2 equiv.	0.19	0.20
EP, kg PO_4^{3-} equiv.	0.80	1.5
AP, kg SO_2 equiv.	0.81	1.0
Pesticides used, dose ha	0.36	0.10
ARU, kg antimony equiv.	1.0	1.2
Land occupation grade 3a Equiv., ha	0.024	0.058
Primary energy usage proportions		
Cultivation	8.5%	15%
Spraying and fertiliser application	2.7%	1%
Irrigation	6.8%	13%
Harvest	10%	14%
Cold storage	49%	48%
Pesticide manufacture	4.8%	0.3%
Fertiliser manufacture	19%	8.0%
Contributors to global warming potential		
CO_2	45%	49%
CH_4	2%	1%
N_2O (direct)	48%	42%
N_2O (via nitrate)	4%	7%

4.2 Oilseed rape

The effects on N on rape were nominally similar to those for bread wheat, with a minimum energy need at about 75% of current N, but the absolute effect was much smaller than for wheat with a reduction of only 1% PE. Because rape is grown primarily for oil rather than protein, land occupation reflects yield reduction.

4.3 Potatoes

A large component of the energy (and other burdens) in potato production is cold storage. As it is a fresh crop and storage requires refrigeration the energy burden amounts to 50% of the total primary energy input (Table 13). However, the GWP per unit energy of main crop potatoes is less that from other

crops, because the energy comes mainly from combustion of fuels to CO_2. Early potatoes have a similar ratio of GWP to PE use as other field crops, since there is no storage. Second earlies have only slightly lower yields than main crop potatoes and so incur about half the burdens. First earlies yield about half that of main crop, and, needing no storage, end up with about the same burdens as main crop.

The burdens of organic and non-organic potato production are much more similar than for wheat, with energy and GWP_{100} being 2% and 13% higher, on average, in organic production (Table 14). Organic pesticide use is 19% of non-organic. This differs from wheat, where none are used, but this represents copper based products for blight control. The similarity of energy use is initially surprising, but results from the following: organic potatoes are lower yielding, but incur the same burdens for field machinery, which being a below-ground crop are relatively high; wastage of organic potatoes is twice as high as non-organic.

Because of the dominance of storage, reducing N input has a much smaller effect on total energy and GWP than with wheat or rape. The minimum energy use is at 92% of the current N rate, but the reduction is less than 0.1%.

Irrigation increases potato yield, but uses extra energy. Increasing the proportion of potatoes irrigated from 0% to 100% increases energy use per tonne by 4%, had no effect on GWP, but decreased land and pesticide use by 21%.

5 Concluding discussion

The results presented (and the working model) allow the burdens of British arable production to be calculated in a flexible way that illustrates the environmental performance of alternative production systems. The analysis is more detailed than others for British crop production. Our results for non-organic production are broadly similar to those from other European studies (Table 15). The values for organic systems differ more widely, with ours being notably higher than Danish results for GWP. It is not clear, however, what systematic differences there are in terms of their farming systems or analysis methods as they do not provide full details. Our analysis does not allow for niche production that cannot be extrapolated to a national level. Our analysis is also based on long-term technically sustainable systems.

The use of system modelling also allows for alternative production systems to be analysed, e.g. reduced tillage or N fertiliser use. Reducing N use on bread wheat by about 25% reduced several impacts per t, but does increase the land occupation requirement. That is not a practical problem if land supply is not limiting (e.g. the existence of set aside), but as demand for biofuels and human food increases, this may not hold for long. The system modelling also shows how the burdens of crop production vary with soil type, for example, wheat grown on sandy soils uses about 20% more energy and causes about 40% more GWP than when grown on clay soils.

Large amounts of energy are used for storing main crop potatoes. There could be potential for reducing energy use here, but it needs a detailed study in its own right.

The results show that greenhouse gas emissions from arable agriculture are far more dependent on N_2O than CO_2 in contrast to most manufacturing industry. That, together with the ill-effects of nitrate and ammonia emissions, leads to the observation that agriculture does not a carbon footprint as much as a C-N footprint. The key to reducing burdens from agriculture thus lies in reducing the need for nitrogen in the production of the target product, e.g. food protein or energy.

Table 15 Comparisons with other studies

	Primary Energy		Global warming potential		Land occupation	
	Non-organic	Organic	Non-organic	Organic	Non-organic	Organic
Wheat						
Denmark[(1)]			710	280	0.15	0.22
Germany[(2)]	2.4	1.5				
This study	2.5	1.7	804	786	0.14	0.44
Rape						
Denmark			1,510			
Germany	6.0	2.5			0.35	
UK other[(3)]	4.7				0.35	
This study	5.4	4.0	1,710		0.31	
Potatoes						
Denmark			160		0.03	
Germany	0.6	0.6				
This study	0.7	0.7	178		0.03	

Other data from ([1] http://www.lcafood.dk/; [2] Röver et al. 2000; [3] Elsayed et al. 2003)

References

Anderson HM, Garthwaite DG, Thomas MR (2002) PUS Report 189: potato stores in GB. Central Science Laboratory, Sand Hutton, York

Anon (1999) Potato storage, FEC2111, Farm energy centre, Stoneleigh Park, Kenilworth

Audsley E (1981) An arable farm model to evaluate the commercial viability of new machines or techniques. J Agric Eng Res 26 (2):135–143

Audsley E (1999) Systematic procedures for calculating agricultural performance data for comparing systems. In agricultural data for life cycle assessments volume 1, proceedings of 2nd European Invitational Expert Seminar on Life Cycle Assessment of Food Products, 25-26 Jan 1999, LEI, The Hague

Audsley E, Alber S, Clift R, Cowell S, Crettaz P, Gaillard G, HausheerJ, Jolliett O, Kleijn R, Mortensen B, Pearce D, Roger E, Teulon H, Weidema B, van Zeijts H (1997) Harmonisation of environmental life cycle assessment for agriculture. Final report, concerted action AIR3-CT94-2028, European Commission, DG VI Agriculture, Brussels

Baggott S, Brown LMR, Murrells T, Passant N, Watterson J (2004) UK greenhouse gas inventory, 1990 to 2002. Annual report for submission under the framework convention on climate change, AEA Technology plc, Culham Science Centre, Abingdon, Oxon., OX14 3ED, UK

Beukema HP, van der Zaag DE (1990) Introduction to potato production. Pudoc, The Netherlands

Bishop CFH, Maunder WF (1980) Potato mechanisation and storage. Farming Press, Ipswich, Suffolk

Brooker DB, Bakker-Arkema FW, Hall CW (1992) Drying and storage of grains and oilseeds. Van Nostrand Reinhold, New York, p 450

Cederberg C (1998) Life cycle assessment of milk production a comparison of conventional and organic farming, SIK-Rapport Nr 643. Göteborg University and the Swedish Institute for Food and Biotechnology, Göteborg

Chamen WCT, Audsley E (1993) A study of the comparative economics of conventional and zero traffic systems for arable crops. Soil & Tillage Research 25(4):369–390

Charles R, Jolliet O, Gaillard G, Pellet D (2006) Environmental analysis of intensity level in wheat crop production using life cycle assessment. Agric Ecosyst Environ 113(1–4):216–225

Defra (2004) http://statistics.defra.gov.uk/esg/publications/auk/2004/6-11.xls

Defra (2005) The British survey of fertiliser practice. Fertiliser use of farm crops for crop year 2004, Defra, London

Elsayed MA, Matthews R, Mortimer ND (2003) Carbon and energy balances for a range of biofuels options, project number B/B6/00784/REP, URN 03/836. DTI, Sheffield

Garthwaite DG, Thomas MR, Dawson A, Stoddart H (2005) Pesticide usage survey report 2002: arable farm crops in Great Britain 2004. Pesticide Usage Survey Group, Central Science Laboratory, Sand Hutton, York

HGCA (2003) Wheat quality data, available at: www.hgca.com (accessed 2004)

Lampkin N, Measures M, Padel S (2002-5) 2002-5 Organic farm management handbook, (4th edition) Institute of rural studies, University of Wales, Aberystwyth

MAFF (2000) Fertiliser recommendations for agricultural and horticultural crops (RB209) (7th edition) The Stationery Office, London

MAFF (1992) UK tables of feed composition and nutritive value for ruminants. (Second edition) Chalcombe Publications

McLean KA (1989) Drying and storing combinable crops (2nd Edition) Farming Pres Ltd, Ipswich

Nellist M (1998) Bulk storage drying of grain and oilseeds, research review (38). Home Grown Cereals Authority, London, p 56

Nix JS (2002-5) Farm Management Pocketbook, (33th (2003) edition) The Andersons Centre, Imperial College London, Wye Campus

Robertson GP, Paul EA, Harwood RR (2000) Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289:1922–1925

Röver M, Murphy DPL, Heinemeyer O (2000) Evaluation of conventional and organic agricultural production in relation to primary energy inputs and certain pollution gas emissions, landbauforschung voelkenrode, sonderheft 211. FAL, Braunschweig

Scotford IM, Burton CH, Phillips VR (1996) Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings. 2. A model to analyse the influence of design parameters on annual costs. J Agric Eng Res 64(2):155–163

Soil Association (2003) Soil Association organic food and farming report 2003. Soil Association, Bristol

Soil Management Initiative (2005) www.smi.org.uk

Smith JU, Bradbury NJ, Addiscott TM (1996) Sundial: a PC-based system for simulating nitrogen dynamics in arable land. Agron J 88(1):38–43

van der Werf HMG, Petit J, Sanders J (2005) The environmental impacts of the production of concentrated feed: the case of pig feed in bretagne. Agric Syst 83(2):153–177

Weatherhead EK, Danert K (2001) Survey of irrigation of outdoor crops in 2001 England, available at: http://www.silsoe.cranfield.ac.uk/iwe/projects/irrigsurvey/2001%20irrigation%20survey%20results%20-%20england.pdf. Accessed 2005.

Weatherhead EK, Knox JW, Morris J, Hess TM, Bradley RI, Sanders CL (1997) Irrigation demand and on-farm water conservation in England and Wales. Report to Ministry of Agriculture, Fisheries & Food (MAFF) Project OC9219, MAFF, London

Williams AG, Sandars DL, Audsley E (2004) Environmental benchmarks of arable farming. Final report to Defra (CSG15) for Project Number ES0112, Silsoe Research Institute, Silsoe

Williams AG, Audsley E, Sandars DL (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main report. Defra Research Project IS0205. Bedford: Cranfield University and Defra. Available on www.agrilca.org and www.defra.gov.uk